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Energy impact of commercial-building envelopes in the sub-tropical climate

K.T. Chan *, W.K. Chow

Department of Building Services Engineering, Kowloon, The Hong Kong Polytechnic University, Hong Kong, China

Abstract

Existing commercial buildings are surveyed and categorized based on the construction characteristics of their envelope. The envelope heat gain and the resulting cooling load demand are analysed with the aid of energy simulation tool DOE-2.1D. The concept of the overall thermal transfer value (OTTV) is applied to study the association of the envelope designs with the cooling requirement, and a modified approach in assessing the effective envelope heat gains under a sub-tropical climate is proposed. The predicted OTTV gives a good indication of the thermal performance of the envelope under a sub-tropical climate. The energy impact and possible range of cooling-load demands, for various envelope designs, under similar internal characteristics and cooling system, are identified. © 1998 Elsevier Science Ltd. All rights reserved.

Nomenclature

A_i	Area of interior surface i (m^2)
A_o	Total gross area of exterior wall (m^2)
BEPI	Building envelope performance index ($kWhm^{-2}$)
CR	Common ratio of the wall response factors
F_o	Inward-flow fraction of the radiation absorbed on the outer pane
H	Number of hours with net envelope heat gain
I_{ab}	Solar energy absorbed by the window and which then flows into the space (Wm^{-2})
I_{DW}	Direct solar radiation on the wall surface or window (Wm^{-2})
I_{SW}	Diffuse solar radiation on the wall surface or window (Wm^{-2})

* Corresponding author. Fax: +852 2774 6156; e-mail: bektc@polyu.edu.hk

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I_{tr}	Solar radiation transmitted through the window (Wm^{-2})
M_W	Opaque-wall mass per unit area (kgm^{-2})
OTTV	Overall thermal transfer value (Wm^{-2})
Q_{rad}	Glass solar gain (kWh)
Q_t	Total heat gain through envelope (kWh)
q_f	Rate of heat gain through window (W)
q_k	Rate of heat flow by conduction (W)
SC	Shading coefficient of fenestration
SF	Solar factor (Wm^{-2})
T_{ia}	Indoor-air temperature (K)
T_{oa}	Outdoor-air temperature (K)
TD_{eq}	Equivalent temperature difference (K)
T_{os}	Outside-surface temperature (K)
t_{dir}	Transmission coefficient for direct solar radiation
t_{dif}	Transmission coefficient for diffuse solar radiation
U_f	Thermal transmittance of fenestration ($Wm^{-2}\ K^{-1}$)
U_w	Thermal transmittance of opaque wall ($Wm^{-2}\ K^{-1}$)
WWR	Window-to-wall ratio
Y_j	Response factors for heat conduction through wall, $j = 0, 1, 2 \ldots$
α	Wall absorptance
α_{difo}	Outside pane absorption coefficient for diffuse radiation
α_{diro}	Outside pane absorption coefficient for direct radiation
ΔT	Temperature difference of outdoor and indoor conditions (K)

1. Introduction

Buildings in the Hong Kong Special Administrative Region, China, with subtropical climates are subjected to high cooling requirements throughout most of the year. Among the electricity consumption in commercial buildings, about 60% is attributable to the operation of air-conditioning systems for comfort cooling. This is about 11.5% of the final energy requirement in Hong Kong, which is much more significant compared with the 6.1% final consumption for commercial space heating and cooling in the member countries of the International Energy Agency [1]. Here the cooling load is particularly dependent on the construction of the building envelope and the weather conditions. To limit the amount of heat gain through the building envelope is obviously an important step for reducing the cooling energy consumption [2].

Following several year's preparation work by the former Hong Kong Government, a Building (Energy Efficiency) Regulation dealing with envelope construction designs stipulating a limit on the overall thermal transfer value (OTTV) has been enacted since 1995 [3]. The OTTV is used to describe the maximum rate of thermal transfer permissible into the building through its wall or roof, due to solar heat gain and outdoor-indoor temperature difference. It was initiated by ASHRAE [4] as a cooling criteria to limit the amount of heat gain through the building fabric, hence the energy consumption for cooling could be reduced. Other Southeast Asia countries, e.g. Singapore [5] and Malaysia [6], are also concerned with the utilization of building energy, particularly on the cooling load resulting from the external heat gains through the building envelopes in air-conditioned buildings. An overall thermal transfer value is stipulated in their building control regulation to evaluate the design on the thermal performance of the building envelopes.

2. Envelope construction characteristics

Almost all commercial buildings in Hong Kong are high-rise. There are two common constructions: the traditional one with concrete frame and load-bearing external wall, and the other with steel or concrete frames plus a non load-bearing external wall. While concrete wall structures with ceramic tile finish or stucco finish are typical for older buildings, curtain walls are common for commercial buildings since the early 1980s. These buildings vary in the types of fenestration, window-to-wall area ratio, materials of opaque wall, with or without insulation, and light or heavy weight constructions.

A total of 64 buildings were surveyed to study the construction characteristics of existing commercial buildings in Hong Kong. The construction details were obtained from in-situ investigation, architectural drawings and from other references for some cases [7]. Most of these buildings were built in the past 10 years, and some were under construction at the time of the study.

The findings show that the external walls can be classified into five types based on the construction methods, designated type I to V as illustrated in Fig. 1. On the other hand, local offices are also graded as A, B or C by the Rating and Valuation Department [8]. Grade A offices have high-quality finishes and good management, Grade C offices have basic finishes and require only minimal management, and Grade B offices are average ones. Type I external-wall construction is traditional, and is found in most Grade C and some Grade B buildings. It has a superficial mass commonly exceeding 300 kgm^{-2} of envelope area, and is characterized by high wall U-values and tinted glass. Twenty per cent of the surveyed buildings belong to this category.

Grade A buildings typically have external wall construction of types II, III, IV or V, which in effect are various forms of curtain wall and account for 80% of the surveyed buildings. Types II and III are medium to heavy-weight curtain wall structures, having an inner heavy-weight concrete layer with spandrel glass or granite panel facade, with or without a fiberglass insulation layer in between. These are most common and account for 68% of the studied buildings. Types IV and V are non-load-bearing constructions, characterized with a light-weight, thick fiberglass insulation layer giving low U-value, highly reflective vision glass, attractive spandrel glass or sometimes an aluminum wall panel facade, and an innermost layer of gypsum board.

A similar investigation for local buildings has been reported but it provides less details, e.g. HKIE OTTV ad-hoc Committee [7]; or for the residential sector, e.g.

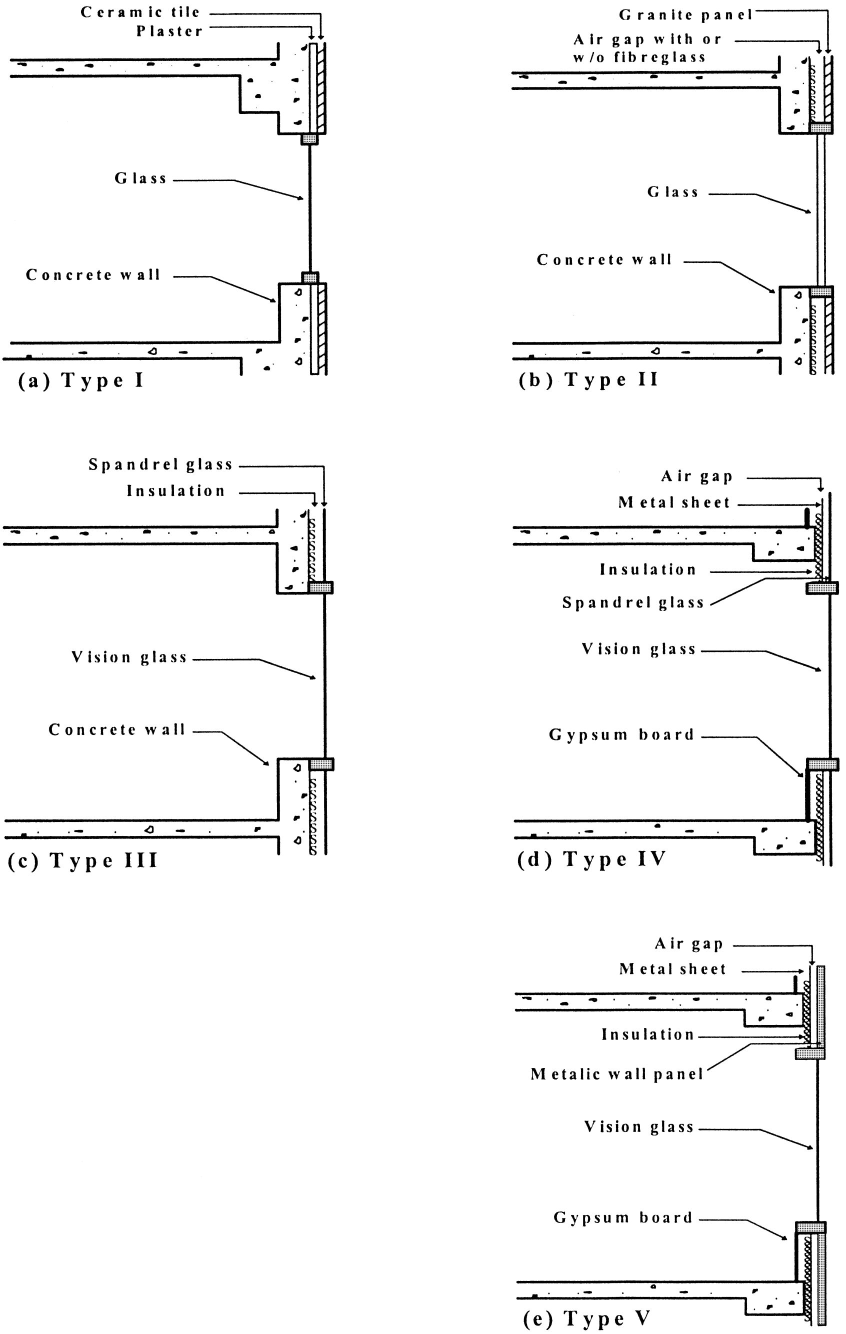

Fig. 1. Construction of external wall.

Lam [9]. The distribution of the sample of surveyed buildings in this study over the range of each key building fabric parameters, including window-to-wall ratio, fenestration-shading coefficient, and opaque wall U-value, are shown in Figs. 2–4. Many commercial buildings, particularly those with curtain walls, are characterized by large window areas. Window-to-wall ratios (WWR) of 0.35–0.7 are common, with the 50% level at 0.47 (i.e. half of the studied buildings have window-to-wall ratios below 0.47, and the other half above). The large window areas are very often coupled with highly-reflective glass having a low shading-coefficient, though the reflective glass is chosen by architects mainly out of aesthetic consideration rather than reduction of solar gain. While most buildings have a shading coefficient of between 0.25 and 0.5, the 50% level is at 0.39, which implies that half of the buildings have a shading coefficient of less than 0.39. Notwithstanding the low shading-coefficient, most of the buildings have single-glazed windows. Among the studied buildings, only five use double-pane glazing, which reflects that this practice is not common locally.

The U-values of the external walls of the studied buildings can be grouped into two categories. The insulated-wall category consists of about 40% of the buildings and each has U-value between 0.5 and $1\,Wm^{-2}\,K^{-1}$. The other 60% have non-insulated walls, where the U-value can be less than $2\,Wm^{-2}\,K^{-1}$ if the wall is massive and has an air layer, but can be as high as $3.4\,Wm^{-2}\,K^{-1}$, which is typical for

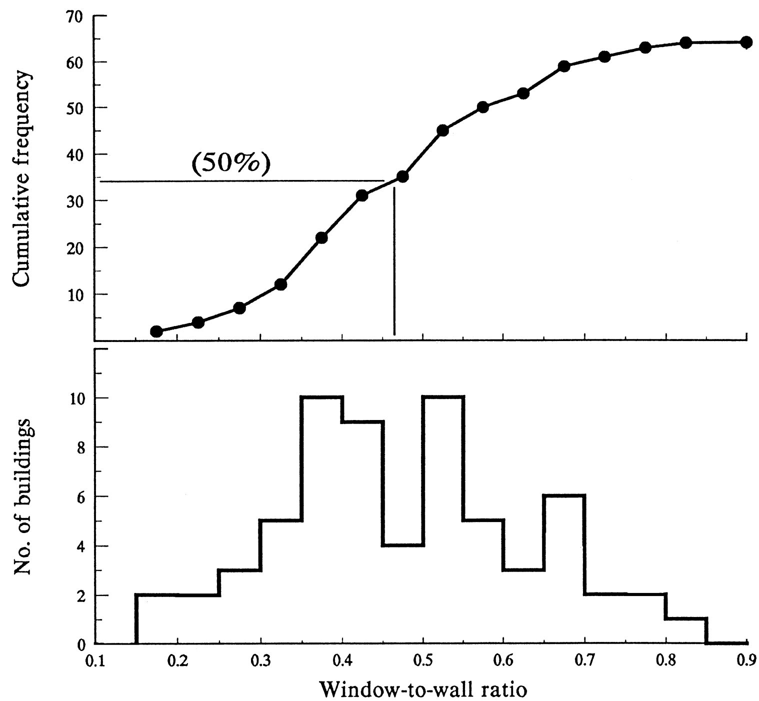

Fig. 2. Window-to-wall ratio distribution.

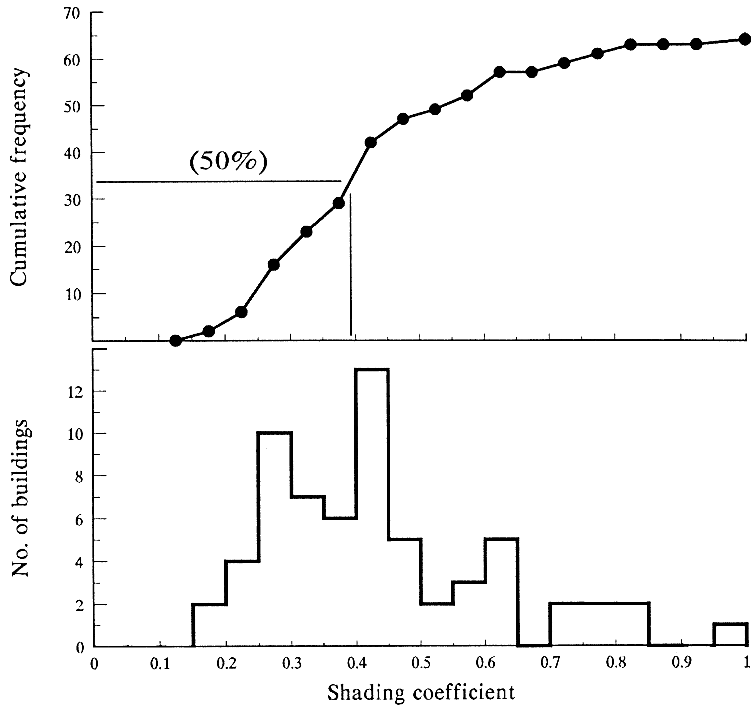

Fig. 3. Window-shading coefficient distribution.

the usual concrete wall with ceramic tile finish. The 50% level is at U-value of 1.9 $\mathrm{Wm^{-2}\ K^{-1}}$. This generally high wall-U-value differs very much from the standard wall constructions in regions with cold climates, where insulation is important for the reduction of heat loss.

Use of heavy-weight concrete (typically ~2400 $\mathrm{kgm^{-3}}$) for the construction of slab and external walls is common in local practice. The majority of the studied buildings have external wall masses in the range of 300–450 $\mathrm{kgm^{-2}}$ of envelope area, owing to a layer of 100–150 mm concrete. A light-weight construction with no concrete layer, but having insulation, is becoming popular in the latest building practices. The mid-level of wall superficial mass densities is 360 $\mathrm{kgm^{-2}}$, i.e. 50% of the studied buildings have wall masses below this value.

The effect of building-envelope parameters on the heat gain and chiller load can be studied by parametric analysis and has been reported by Chow and Chan [2].

3. Envelope heat transfer and the OTTV equation

The hour-by-hour heat conduction and solar radiation through the building walls and windows were determined with the building energy simulation tool DOE-2.1D

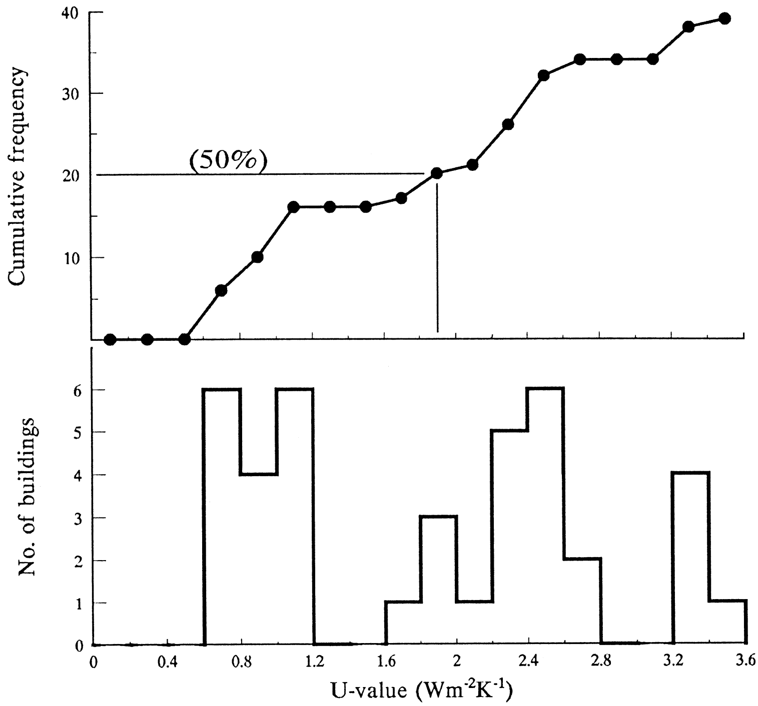

Fig. 4. Wall U-value distribution.

[10]. The transient heat conduction through the wall is solved using the response-factor method [11] and principle of superposition, with time-series impulse transfer function to determine the transient behavior of a building. One-dimensional heat flow is assumed for the heat flows by conduction through the considered wall with finite thermal-capacity. The heat flux responses to temperature excitation at the outside surface are determined at hourly intervals. The rate of heat flow from the wall's inside-surface to the room air at time t, $q_k(t)$, is calculated for each of the 8760 h in a year via:

$$q_k(t) = A_i\{Q_Y(t) + Y_0[T_{os}(t) - T_{ia}]\} \tag{1}$$

where

$$Q_Y(t) = CR[Q_Y(t-1) - S_Y(t-1)] + S_Y(t) + Y_k[T_{os}(t-k) - T_{ia}] \tag{2a}$$

$$S_Y(t) = \sum_{j=1}^{j-1}[T_{os}(t-j) - T_{ia}]Y_j \tag{2b}$$

The rate of heat entering the space through the window is calculated for a standard clear glass from the direct (I_{DW}) and diffuse (I_{SW}) solar radiations on the window surface, the transmission coefficients (t_{dir}, t_{dif}) and absorption coefficients ($\alpha_{dir}, \alpha_{dif}$) for direct and diffuse radiation. For a window characterized with shading coefficient SC, the transmitted and absorbed solar energies flowing inward at each of the 8760 h in a year are calculated respectively as:

$$I_{tr} = [I_{DW} \times t_{dir} + I_{SW} \times t_{dif}]\mathrm{SC} \tag{3}$$

$$I_{ab} = [I_{DW} \times \alpha_{diro} \times F_0 + I_{SW} \times \alpha_{difo} \times F_0]\mathrm{SC} \tag{4}$$

Adding the conduction heat due the to outdoor–indoor temperature difference, the rate of heat entering the space through the window becomes:

$$q_f = I_{tr} + I_{ab} + U_f(T_{oa} - T_{ia}) \tag{5}$$

In using the overall thermal transfer value as an indicator of the thermal performance of building envelopes, it is most important to derive the coefficients of the OTTV equation which can address the interaction of the local building construction characteristics and climatic conditions. Unlike the approaches adopted by others, e.g. Chou and Lee [12] and Deringer and Busch [13], components of heat gain and loss through the envelope are analyzed in this work with the concept of differentiating between hours of net gain and hours of net loss [14]. The number of hours with net envelope gain (*H*) represents those hours during which there is more heat flow through the external wall *into* the building than *out of* the building. It is a viable parameter for assessing the effective total envelope gain and the average rate of heat gain through the envelope and indicated by the OTTV.

Heat gains are used for the analysis of the thermal performance of the building skin. This approach has the advantage over the use of the annual building cooling load by Chou and Lee [12], which cannot account for hours with a heat loss occurring to the surrounding, though the latter is not a problem in the tropical climate. It also has the advantage over the use of an annual chiller load [13] which involves the operational behavior of the air-conditioning system.

Derivation of the OTTV equation was done using the heat-gain components obtained from a sample of 40 commercial buildings with constructions representing the prevailing local-building-envelope characteristics. Each of these envelope constructions is represented in turn by a standardized square shape high-rise building with sides of 36 m. The use of a standardized shape in the simulation is necessary in order to enable the thermal effects of different envelope constructions to stand out. The hour-by-hour heat conduction and solar radiation components through the building walls and windows are compiled to determine the net total envelope heat gain or loss for each hour and the number of hours with net envelope heat gain (*H*) throughout the year. These buildings have envelope characteristics that adequately cover the likely range of each key envelope parameter in local commercial buildings. This strategy of using actual envelope constructions of a large sample of buildings has the advantage of preserving the effect of combinations of various parameters in real buildings, while the requirement of the factorial analysis technique covering the likely range of each key parameter is also satisfied.

In each case, the year-round total envelope heat-gain is summed for all hours with net envelope heat gain, excluding those hours with net heat loss through the envelope from inside to outside. The magnitude of H is compiled for each building with a total gross area of exterior wall A_o in the sample being studied, and averaged to give a mean number of hours of net envelope heat gain ($\bar{H}$). The OTTV can then be calculated by averaging the effective total envelope heat gain over $\bar{H} \times A_o$. Each of the sample buildings is also coupled to a variable air-volume system to determine the chiller load, which is the energy extracted by the air-conditioning system to offset the instantaneous cooling load resulting from external and internal heat gains. With identical internal load characteristics, the changes in the chiller load among the buildings indicate the extent of influence of the envelope's heat gain on the cooling demand.

For a given set of envelope parameters, the predicted mean value of OTTV (labeled as $\mathrm{OTTV_m}$) can be expressed as:

$$\mathrm{OTTV_m} = a + b_1X_1 + b_2X_2 + b_3X_3 \tag{6}$$

where b_1, b_2, and b_3 represent the equivalent temperature difference (TD_{eq}) across the opaque wall, the temperature difference (ΔT) for conduction across the window, and the solar factor (SF) for solar radiation through the window, respectively; X_1, X_2 and X_3 are the products of the building-envelope's features of window-to-wall ratio (WWR), shading coefficient of fenestration (SC), U-value of opaque wall (U_{w}) and fenestration (U_{f}), representing $(1 - \mathrm{WWR})U_{\mathrm{w}}, (\mathrm{WWR})U_{\mathrm{f}}$ and $(\mathrm{WWR})\mathrm{SC}$, respectively.

The coefficients b_1, b_2, and b_3 are derived by multiple regression with the method of least-squares fitting, and are determined to be 2.8 (°C), −0.36 (°C) and 118 ($\mathrm{Wm^{-2}}$), respectively. Accordingly the regression equation, i.e. the final form of the OTTV equation, becomes:

$$\mathrm{OTTV} = 2.8(1 - \mathrm{WWR})U_{\mathrm{w}} - 0.36(\mathrm{WWR})U_{\mathrm{f}} + 118(\mathrm{WWR})SC \tag{7}$$

The coefficient of multiple determination, R^2, measures the degree of association in the dependent variable OTTV explained by the fitted regression equation to the independent variables (i.e. the envelope parameters). R^2 is found to be 0.988, which implies that 98.8% of the variance in the OTTV has been explained by the fitted regression Eq. (7) relating OTTV to the variables $(1 - \mathrm{WWR})U_{\mathrm{w}}$, $(\mathrm{WWR})U_{\mathrm{f}}$, and $(\mathrm{WWR})\mathrm{SC}$.

Student's t values are used for test of confidence and significance of the regression coefficients b_1, b_2 and b_3 (i.e. $T\mathrm{d_{eq}}, \Delta T$ and SF). These also measure the separate effects of each of the independent variables $(1 - \mathrm{WWR})U_{\mathrm{w}}, (\mathrm{WWR})U_{\mathrm{f}}$ and $(\mathrm{WWR})\mathrm{SC}$ on the dependent variable OTTV. From the calculated t values, it can be seen that the solar factor (SF) has the largest and statistically highly-significant effect on the OTTV, followed by the equivalent temperature difference (TD_{eq}) for the exterior wall. The coefficient $b_2(\Delta T)$ associated with conduction through window does not have a noticeable statistical influence on the OTTV. This is because the local climate includes hours of high outdoor-air temperature with conductive heat gain as well as hours of cool weather with conductive heat loss through the window, and the effect is neutralized in the OTTV, which indicates the year-round average heat transfer through the envelope. Yet, at times of outdoor temperatures lower than the room temperature, there is often a net cooling load because of the high internal heat gain. The combined effect of the local climate and the high internal-load characteristics of office buildings does not favour the use of double glazing because of its low U-value [15]. However, the practical significance of window U-value on reducing the peak heat gain and peak load, that in turn determines the required installed cooling capacity and fan size, must not be overlooked.

4. Thermal performance of building envelopes

The thermal performance of an envelope construction can be indicated by the term Building Envelope Performance Index (BEPI) with unit of kWh per square metre of envelope area. It is the effective total heat-gain obtained by summing the wall conduction gain, glass conduction gain and glass solar-radiation gain for all hours with the net envelope gain and normalized over the total exterior wall area, expressed in $kWhm^{-2}$. This term can be interpreted as an index for a particular form of envelope construction, indicating the possible amount of heat gain per unit area of the exterior wall that constitutes the cooling requirement throughout a year. The correlation of the predicted OTTV by Eq. (7) with the BEPI is illustrated in Fig. 5, including the 95% level of confidence. With this, the OTTV of any envelope construction can be computed with Eq. (7); then the corresponding BEPI (in $kWh\,m^{-2}$) and the year-round effective total heat gain Q_t (in kWh) through the envelope can be calculated as:

$$Q_t = \text{BEPI} \times A_o = (0.075 + 3.64 \times \text{OTTV})A_o \tag{8}$$

Comparison of the energy efficiency of a building can be made by referring to the sum of the thermal demand and the electrical demand, the latter being the average rate of electrical energy consumption over a year. In this report, the electrical consumption by the cooling plant is not used for comparison among buildings, so as to avoid the influence of plant efficiency. Instead, the chiller load is used as the basis for comparison of the thermal effectiveness of different envelope constructions. It represents the energy extracted by the air-conditioning system to offset the instantaneous cooling load resulting from external and internal heat gains, as a load on the chiller plant. This chiller load is the cumulative amount for a year, and can be divided by the total treated floor area to give a normalized value. Such a normalized chiller load is termed the chiller load demand in this report, with unit of $kWh\,m^{-2}$.

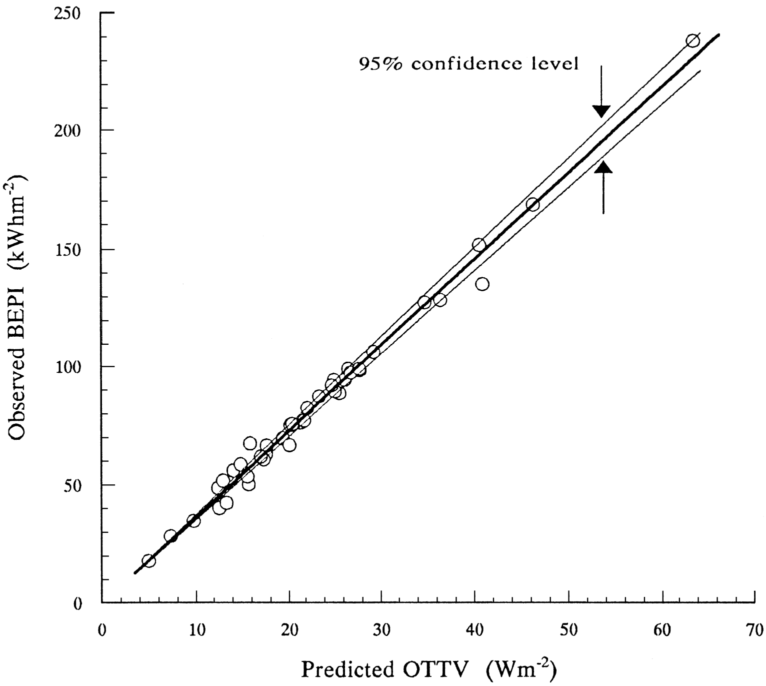

Fig. 5. Correlation of the predicted OTTV of buildings with the observed BEPI.

The chiller load demand for each of the 40 observations is obtained from the building and system simulation with DOE-2. These are plotted against the predicted OTTV in Fig. 6, the result of which indicates that the effective total envelope gain and the OTTV defined in Eq. (7) can provide a good estimation of the change in the chiller load due to differences in the envelope construction. Hence, in addition to assessing the envelope's heat gain, the predicted OTTV can also be used to estimate the likely amount of chiller load demand in $kWhm^{-2}$, as:

$$\text{Chiller load demand} = C_1 + C_2(\text{OTTV}) \tag{9}$$

where C_1 and C_2 are found to be 164 and 1.48, respectively, for office buildings with prescribed building operation and air-conditioning system characteristics as given in Table 1. C_1 represents the component of the chiller load attributable to the internal load and ventilation load, which are independent of the envelope construction. C_2 gives the rate of change of chiller load with the OTTV. Eq. (9) can only be used with the understanding that the calculated chiller-load demand provides a reference only, as it is constrained by the prescribed specification of the air-conditioning system and the building's operation-patterns. The actual load is expected to vary for different internal constructions and furniture, different internal load intensities, different building operation patterns and particularly different air-conditioning system designs.

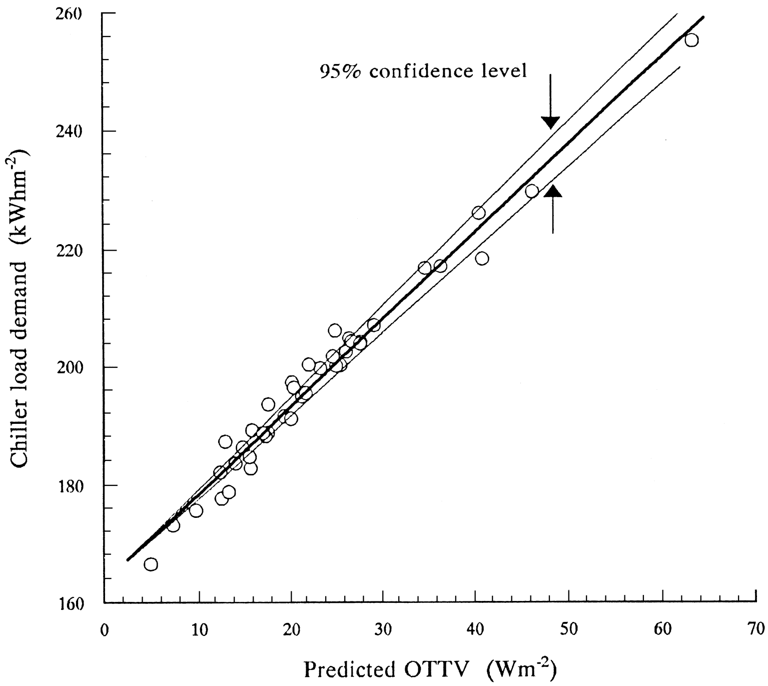

Fig. 6. Correlation of the predicted OTTV of buildings with the chiller load demand.

5. Influence of envelope construction on cooling requirement

It has been shown earlier that the solar factor has a much larger impact on the OTTV than the other coefficients. Consequently, the last term in Eq. (7) containing the envelope parameter WWR$\times$SC will account for a significant portion of the calculated OTTV. Sullivan et al. [16] called this product of window-to-wall area ratio and shading coefficient the solar aperture, and reported that the incremental electricity consumption due to solar gain was nearly linear with increasing solar aperture. This is further investigated by comparing the envelope heat gain for all hours with the net gain in a year with changes of the solar aperture for the sample of 40 observations, illustrated in Fig. 7. The building envelope's performance index (BEPI), which is the effective total envelope heat gain normalized over the envelope area, and the chiller load demand are plotted against the solar aperture WWR$\times$SC in Fig. 8.

In Fig. 7, the amount of the solar radiation gain, expressed as a percentage of the effective total envelope heat gain, is compared against the solar aperture WWR $\times$ SC. It should be noted that this percentage is often greater than 100, because the cumulative window conductive component is often negative (i.e. a heat loss occurs) so making the absolute total envelope gain less than the solar component. There is no linear relationship between the two parameters. However, for most

Table 1
System characteristics and operating schedule of buildings

Air-conditioning system	System type = VAV Outside air = 7 litre/s/person Cooling set-point = 25.5°C Heating set-point = 22°C Chiller plant = Air-cooled centrifugal Chiller COP = 3.2 (at nominal capacity)
Infiltration	0.5 and 0.1 air change per h at the perimeter zones during fans OFF and ON, respectively
Lighting and electrical equipment	Lighting power intensity = 20 Wm^{-2} Ratio of heat-of-light to space = 0.8 Equipment power intensity = 12 Wm^{-2}

		Operating schedule			
Hour		Occupancy [a]	Lighting [a] (perimeter)	Lighting [a] (interior)	Fans
1–7	Weekday	0	0.05	0.05	Off
8		0.05	0.1	0.1	Off
9		0.4	0.5	0.5	On
10		0.95	0.9	1	On
11		0.95	0.9	1	On
12		0.95	0.9	1	On
13		0.95	0.9	1	On
14		0.45	0.8	0.9	On
15		0.95	0.9	1	On
16		0.95	0.9	1	On
17		0.95	0.9	1	On
18		0.5	0.8	0.8	On
19		0.25	0.5	0.5	On
20		0.1	0.3	0.3	Off
21		0.05	0.2	0.2	Off
22–24		0	0.05	0.05	Off
1–7	Saturday	0	0.05	0.05	Off
8		0.05	0.1	0.1	Off
9		0.3	0.5	0.5	On
10–13		0.6	0.75	0.8	On
14–17		0.1	0.2	0.2	Off
18		0.05	0.1	0.1	Off
19–24		0	0.05	0.05	Off
1–9	Sunday	0	0.05	0.05	Off
10–17		0.05	0.1	0.1	Off
18–24		0	0.05	0.05	Off

[a] The decimal fractions denote percentage of maximum occupancy or lighting power.

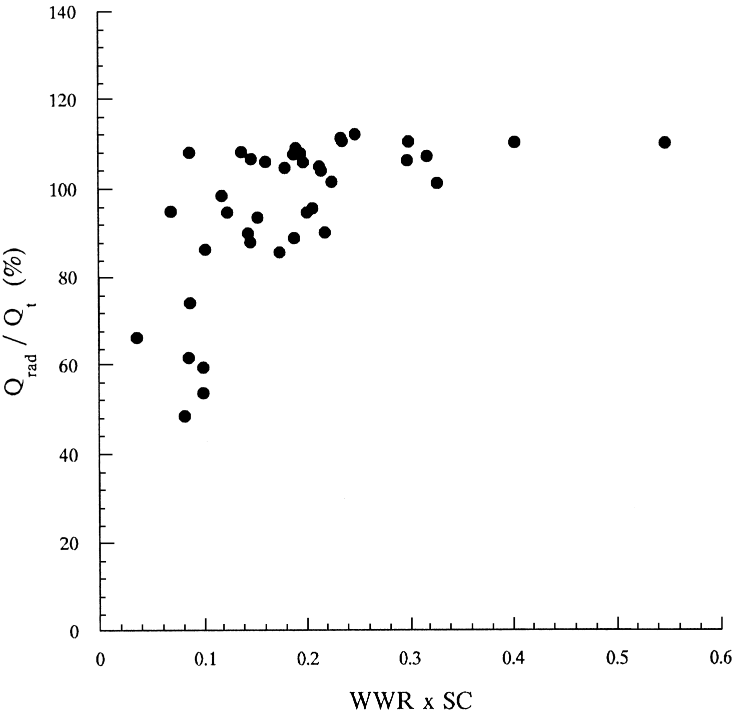

Fig. 7. Amount of solar radiation component out of the effective total envelope heat gain.

of the observations, the fraction $Q_{\text{rad}}/Q_{\text{t}}$ exceeds 80%, except when the glass-shading coefficient is very low and WWR $\times$ SC is less than 0.1. This indicates that, over a wide range of values of WWR $\times$ SC, the solar-radiation gain component remains accountable for a substantial portion of the effective total envelope gain. Close association of the solar aperture with the BEPI and the chiller load is observed as illustrated in Fig. 8.

Another point of interest is the association of the predicted OTTV with the peak cooling-load, which will in turn determine the fan power and the installed chiller-plant capacity. This is illustrated in Fig. 9. From the 40 observations, the peak space-cooling load increases proportionally with larger OTTV, with a correlation coefficient of 0.979. The intercept of the regression line with the vertical axis indicates the amount of space load resulting from the prescribed internal load characteristics, whereas the weather-dependent component varies linearly with the predicted OTTV. If the air-side is a constant air volume system, this peak space load will determine the fan size and the air transport energy. Even if a variable-air-volume system is used, the fan has to be sized on the maximum flow rate at the peak space-load, and the fan part-load efficiency will be penalized for larger installed fan capacity. It follows that building envelopes giving higher OTTV values will imply the air-conditioning system requires a larger fan capacity, has poorer

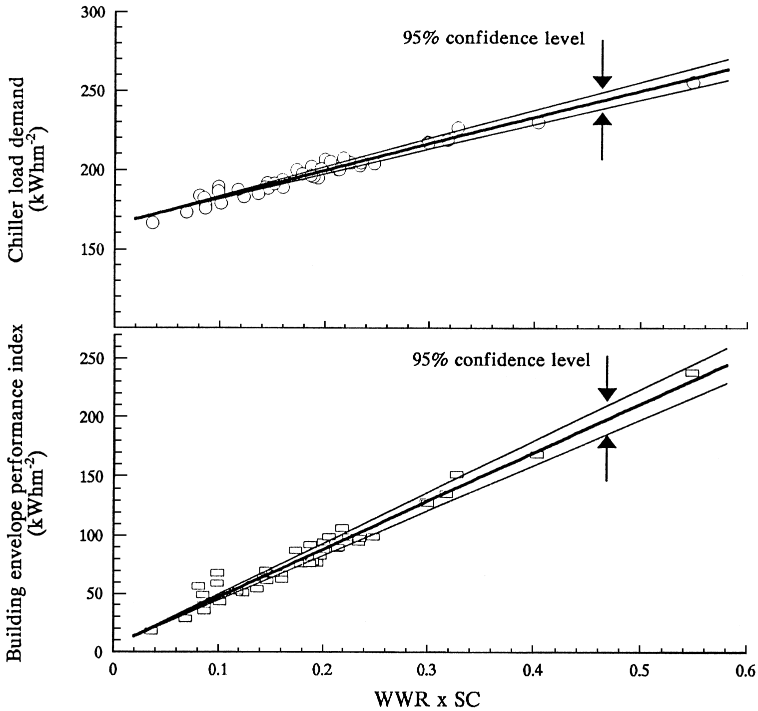

Fig. 8. Significance of WWR×SC on the envelope's heat gain and chiller load.

part-load efficiency and consumes more energy, not to mention the higher initial equipment-cost.

A consequence of increased space load is the corresponding increase in the chiller load, and the peak chiller load governs the required installed capacity of the chiller plant and the part-load plant efficiency. The association between the peak chiller load and the predicted OTTV is also shown in Fig. 9. There does not exist a simple linear relation between these two dependent variables. Though a higher OTTV will imply more space load, that will inevitably lead to larger chiller load, the peak chiller load is also dependent on a number of other weather-dependent and non-weather-dependent parameters. The ventilation load is usually a large component of the total cooling load for hot and humid regions, so that the enthalpy of the outdoor air is a significant factor influencing the magnitude and time of occurrence of the peak chiller load. Also, after system shut-down, the air infiltration will impose an extra load on the chillers at system start-up, particularly if the air is humid. The influence of the OTTV on the peak chiller load is therefore masked by these other factors.

The ultimate purpose of controlling the overall thermal transfer value of a building envelope is to reduce the cooling load, hence cutting down the chiller load and consequently the energy consumption. The magnitude of this envelope load varies in individual buildings, depending on the construction of the building skin and the

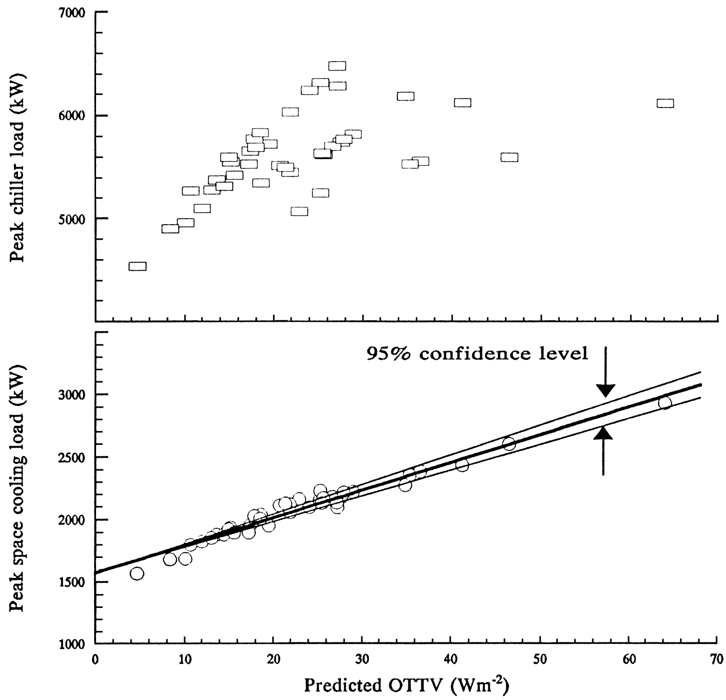

Fig. 9. Correlation of OTTV with the peak load.

thermal/physical properties of the constituent layers. The extent of influence of an envelope's construction on the cooling energy requirement is illustrated in Fig. 10 for the sample of 40 building envelopes along with the predicted OTTV. The difference in the year-round chiller-load demand among the cases is merely due to differences in the envelope constructions.

Among the 40 surveyed building envelopes, the highest chiller load demand is 255 $kWhm^{-2}$ of air-conditioned floor area corresponding to an OTTV of 64 $W\,m^{-2}$, and the lowest chiller load is 167 $kWh\,m^{-2}$ corresponding to a OTTV of 4.7 $W\,m^{-2}$. In these two extremes the building of high OTTV has also much larger peak cooling load and requires an installed chiller plant size of 1.35 times of the cooling plant capacity of the low OTTV building. The surveyed building with the worst envelope has a 25% increased chiller-load demand over an average reference building, and its envelope load accounts for 32% of its year-round cooling energy consumption.

Fig. 10 also shows the thermal performance of a highly energy-intensive envelope construction and an energy-effective envelope construction. The energy intensive form comprises an unfavorable combination of observed envelope features, with single glazing, WWR = 0.79, SC = 0.8, $U_w = 3.46\ W\,m^{-2}K^{-1}$, $M_w = 303\ kg\,m^{-2}$ and $\alpha = 0.85$. The energy effective form is obtained by a favorable combination of envelope features found among the surveyed buildings, with double glazing,

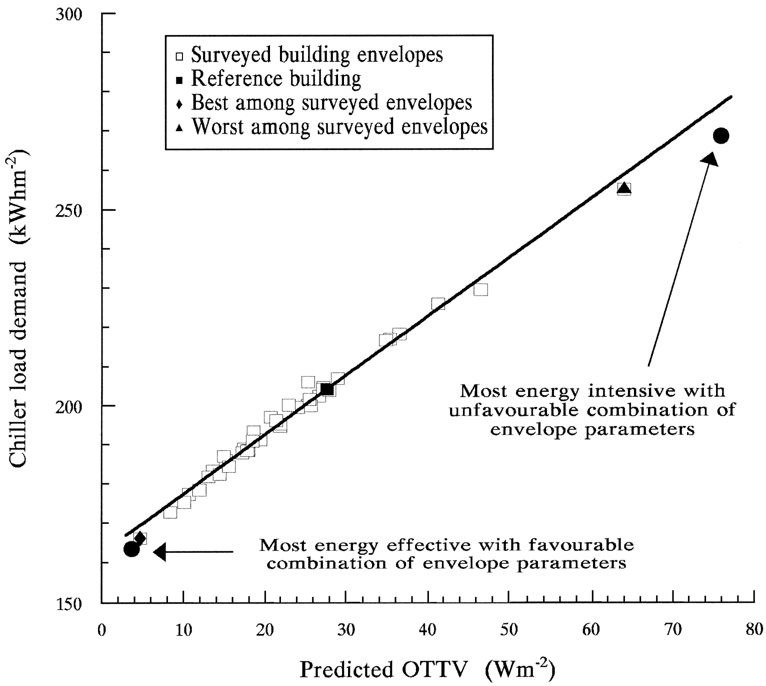

Fig. 10. Possible range of OTTV and the corresponding chiller-load demand.

WWR $= 0.24$, $SC = 0.14$, $M_w = 689\ \mathrm{kg\,m^{-2}}$, $\alpha = 0.3$ and $U_w = 1.07\ \mathrm{Wm^{-2}\,K^{-1}}$. For the "make-up" case of the unfavorable combination of envelope parameters, the chiller load demand is further increased to $268.5\ \mathrm{kWhm^{-2}}$. The diagram also shows the possible range of OTTV predicted by Eq. (7) as encountered for commercial buildings.

6. Conclusions

The envelope construction characteristics of commercial high-rise buildings have been investigated and categorized. The heat transfer and thermal performances of these envelope constructions are studied using the building energy simulation tool DOE-2. The results indicated that the different envelope constructions for buildings in the sub-tropical climate of Hong Kong have substantial effects on the magnitude of the external heat gains and cooling-energy requirement. Designing a building with energy-effective envelope will reduce the external heat gain and cut the cooling energy consumption by as much as 35% compared with a poor envelope design. It will also bring about a credit on the peak space-cooling load, which can be reduced by 47% compared with an energy-intensive envelope design, so allowing the installation of a cooling plant of smaller capacity.

The concept of OTTV is applied, with a new but logical approach of assessing the effective envelope heat gain and cooling demand. As a characteristic of office buildings with high internal-load intensities in a sub-tropical climate, there are hours of net heat loss through the building envelope but accompanied by a cooling demand in the room, and the net heat loss during these hours contributes to reduce the cooling-energy requirement. The inclusion of envelope heat transfer in all these hours will have a canceling effect on summarizing the envelope heat gains accountable for the cooling demand. On the other hand, it is not appropriate to count only those hours of the summer season and ignore the envelope performance in the intermediate seasons. The concept of summarizing the envelope heat transfer components algebraically for all hours of net heat gain in a year is adopted to evaluate the thermal performance of different envelope constructions. Accordingly, the impacts of building-envelope's parameters are evaluated and an OTTV equation is derived by multiple regression from the simulated net total envelope heat-gains.

Heat transfer through building envelope in the sub-tropical climate is dominated by the solar radiation gain as indicated in Fig. 7. This is governed by the solar aperture and is found to be above 80% of the effective annual envelope heat gain for 34 buildings out of the 40 studied cases. Conduction due to the outdoor indoor temperature difference does not contribute much to the effective annual envelope gain, but is significant for the peak cooling load.

The extent of influence of the envelope construction on the cooling-energy requirement is illustrated in Fig. 10. Change in the cooling load resulting from the envelope design is substantial, as indicated by the range for the normalized chiller-load demand from 167 to 255 kWhm^{-2} among the surveyed buildings. There is also a high correlation of 0.99 between the predicted OTTV and the chiller-load demand. Hence, using OTTV as a criterion is a valid measure to ensure an energy-effective design of building envelope, and can be a practically enforceable item of legislation for building energy control. Results derived are not only useful in Hong Kong, but also applicable to other cities having similar sub-tropical climates.

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